Next-Generation Global and Mesoscale Atmospheric Models

Francis X. Giraldo
Naval Postgraduate School
Monterey, CA 93943-5216
phone: (831) 656-2293 fax: (831) 656-2355 e-mail: fxgirald@nps.edu

LONG-TERM GOALS

The long-term goal of this research is to construct the Navy's next-generation global numerical weather prediction (NWP) models using new numerical methods specifically designed for distributed-memory and vector computers. To take full advantage of distributed-memory computers, the global domains of our models are partitioned into local sub-domains, or elements, which can then be solved independently on multiple processors. The numerical methods used on these sub-domains are local in nature, high-order accurate, and highly efficient. Using these ideas we are developing global and mesoscale atmospheric models that should be able to improve upon the operational models currently used by the Navy.

OBJECTIVES

The objective of this project is to construct new high-order local methods for the Navy's next-generation global and mesoscale NWP models. The high-order accuracy of these methods will ensure that the new model yields the same accuracy as the current global spherical harmonics model and better accuracy than the current mesoscale finite difference model. The objective is to achieve this accuracy while increasing the geometric flexibility to use any grid as well as to increase the efficiency of these models on large processor-count distributed-memory computers.

APPROACH

To meet our objectives we explore:

1. spectral element (SE) and discontinuous Galerkin (DG) methods,

2. semi-implicit (SI) and semi-Lagrangian (SL) time-integrators, and

3. various forms of the governing equations in order to maximize accuracy, efficiency, stability, and conservation properties.

The power of SE and DG methods is that they are high-order accurate, like spherical harmonics methods, yet are completely local in nature – meaning that the equations are solved independently within each individual element and processor. Furthermore, high-order methods have minimal dispersion error which is an important property for capturing fine-scale atmospheric phenomena (e.g., tropical cyclones, Kelvin and Rossby waves). In addition, semi-implicit (SI) and semi-Lagrangian (SL) methods offer vast improvements in efficiency due to the longer time steps that they permit. Before developing a computer model, it is important to first analyze the best set of equations for

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **Next-Generation Global And Mesoscale Atmospheric Models**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Monterey,CA,93943-5216**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

The long-term goal of this research is to construct the Navy?s next-generation global numerical weather prediction (NWP) models using new numerical methods specifically designed for distributed-memory and vector computers. To take full advantage of distributed-memory computers, the global domains of our models are partitioned into local sub-domains, or elements, which can then be solved independently on multiple processors. The numerical methods used on these sub-domains are local in nature, high-order accurate, and highly efficient. Using these ideas we are developing global and mesoscale atmospheric models that should be able to improve upon the operational models currently used by the Navy.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

representing the dynamics of the atmosphere. We have analyzed in detail various forms of the equations.

WORK COMPLETED

NSEAM Global Hydrostatic Model. The bulk of the work this year on NSEAM was supporting the effort of NRL Monterey to include the NOGAPS physical parameterization into the NSEAM dynamical core. For example, one problem that arose during this phase of the work was that the moisture field exhibited the so-called "spectral rain" near the boundaries of the element edges. A simple one-dimensional analysis revealed the source and the easiest remedy was found to be hyper-viscosity operators similar to those used in current spherical harmonics models. However, this required constructing high-order Laplacian operators which are not so straightforward to build in a finite element model.

Another part of this work involved constructing the so-called ITCZ (inter-tropical convergence zone) grid which was used to study Madden-Julian oscillations (MJO) within the aquaplanet experiments used to test NSEAM with full moist physics. This grid uses high resolution near the equatorial region and, it was conjectured, would result in a sharper MJO signal. These results are discussed in the NRL Monterey reports and a paper (with Maria Flatau) was submitted to a journal (see ref. [1]). The PI (Giraldo) worked on developing the numerical model along with the grids and the interpolation stencils required to output the fields to the NOGAPS format.

One portion of the work regarding the NSEAM dynamics involved the construction of a nonhydrostatic DG version of the NSEAM dynamical core. The collaboration with Dr. Matthias Läuter (of the Alfred-Wegener Institute in Potsdam Germany) through ONR Global VSP resulted in a paper on a DG barotropic model on the sphere (see ref. [2]). This collaboration will continue and it is expected that it will result in a DG baroclinic model by the end of 2008.

Mesoscale Nonhydrostatic Atmospheric Models. The majority of the time this year was spent on analyzing various forms of the governing equations of motion as well as developing numerical models based on all these equation sets. Specifically we analyzed the following equations: Set 1 is defined as follows

$$
\begin{aligned}
&\frac{\partial \pi}{\partial t} + \mathbf{u} \bullet \nabla \pi + \frac{R}{c_v} \pi \left(\nabla \bullet \mathbf{u} \right) = 0 \\
&\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \bullet \nabla \mathbf{u} + c_p \theta \nabla \pi = -f \left(\mathbf{k} \times \mathbf{u} \right) - g \mathbf{k} + \mu \nabla^2 \mathbf{u} \\
&\frac{\partial \theta}{\partial t} + \mathbf{u} \bullet \nabla \theta = \mu \nabla^2 \theta
\end{aligned}
$$

where the solution vector is Exner pressure, velocity, and potential temperature. Set 1 is the equation set used in the U.S. Navy's mesoscale model COAMPS and a similar form is also used in the German meoscale model LM. The main problem with this equation set is that it cannot conserver either mass or energy.

Set 2 is defined as follows

$$
\begin{aligned}
&\frac{\partial \rho}{\partial t} + \nabla \bullet \mathbf{U} = 0 \\
&\frac{\partial \mathbf{U}}{\partial t} + \nabla \bullet \left(\frac{\mathbf{U} \otimes \mathbf{U}}{\rho} + P\mathbf{I}_2 \right) = -f(\mathbf{k} \times \mathbf{U}) - \rho g \mathbf{k} + \nabla \bullet (\mu \rho \nabla \mathbf{u}) \\
&\frac{\partial \Theta}{\partial t} + \nabla \bullet \left(\frac{\Theta \mathbf{U}}{\rho} \right) = \nabla \bullet (\mu \rho \nabla \theta)
\end{aligned}
$$

where the solution vector is density, momentum, and density potential temperature. Set 2 is the form used in WRF. This form is very attractive because it conserves mass but not energy.
Set 3 is defined as

$$
\begin{aligned}
&\frac{\partial \rho}{\partial t} + \nabla \bullet \mathbf{U} = 0 \\
&\frac{\partial \mathbf{U}}{\partial t} + \nabla \bullet \left(\frac{\mathbf{U} \otimes \mathbf{U}}{\rho} + P\mathbf{I}_2 \right) = -f(\mathbf{k} \times \mathbf{U}) - \rho g \mathbf{k} + \nabla \bullet \mathbf{F}_u^{visc} \\
&\frac{\partial E}{\partial t} + \nabla \bullet \left(\frac{E + P}{\rho} \mathbf{U} \right) = \nabla \bullet \mathbf{F}_e^{visc}
\end{aligned}
$$

where the solution vector is density, momentum, and density total energy. This equation set is not used in atmospheric modeling but is the equation of choice in computational fluid dynamics (CFD). This set is very attractive because it is fully conservative regardless of whether the flow is inviscid or viscous. One question about this set, however, is whether it can be coupled to existing physical parameterization packages which rely on potential temperature and not energy. Using these three equation sets we developed 5 different x-z slice mesoscale models in order to compare the spectral element and discontinuous Galerkin methods and to see how these models behaved under a series of test cases including sharp front simulations and nonhydrostatic flow over mountains. This work resulted in a peer-reviewed article which was submitted this year (see ref. [3]).

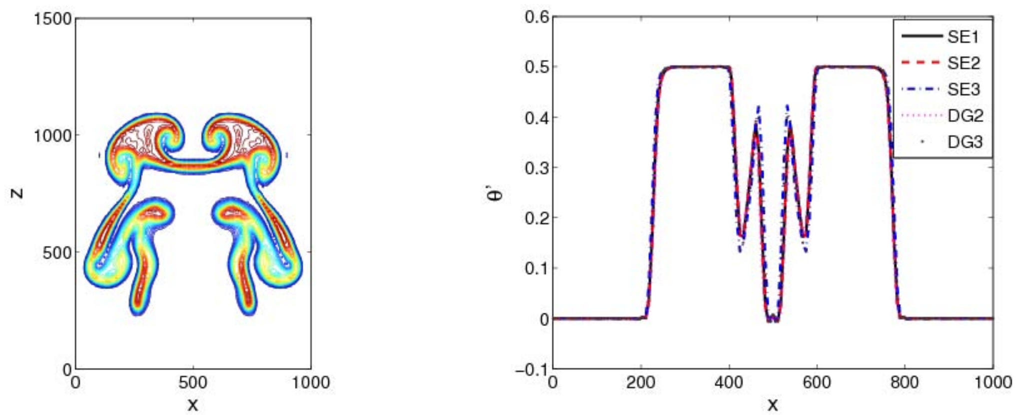
In addition, we developed hybrid Eulerian-Lagrangian semi-implicit (HELSI) time-integrators for one of the SE mesoscale models (for set 1); this work was carried out by Air Force Lt. Tom DeLuca during his Master's thesis project (see refs. [4] and [5]). It is expected that this work will be submitted to a journal and will continue as the PhD dissertation of Tom DeLuca.

In collaboration with Marco Restelli (an ONR Global VSP visitor working on his PhD dissertation with Prof. Giraldo) the PI (Giraldo) was able to developed the first semi-implicit time-integrator for any DG model. This result is very important because, until this point, DG models were not competitive with SE models in terms of efficiency because no one had figured out how to construct semi-implicit time-integrators for this method. This work has been submitted to a journal (see ref. [6]).

Another interesting work involved the development of high-order non-reflective boundary conditions for the mesoscale models. This work is being conducted by Air Force Maj. John Dea for his PhD dissertation. The results are still quite preliminary but it looks possible to be able to absorb all outgoing waves without any reflections while using very few points. This work has been submitted to a journal (see ref. [7]).

RESULTS

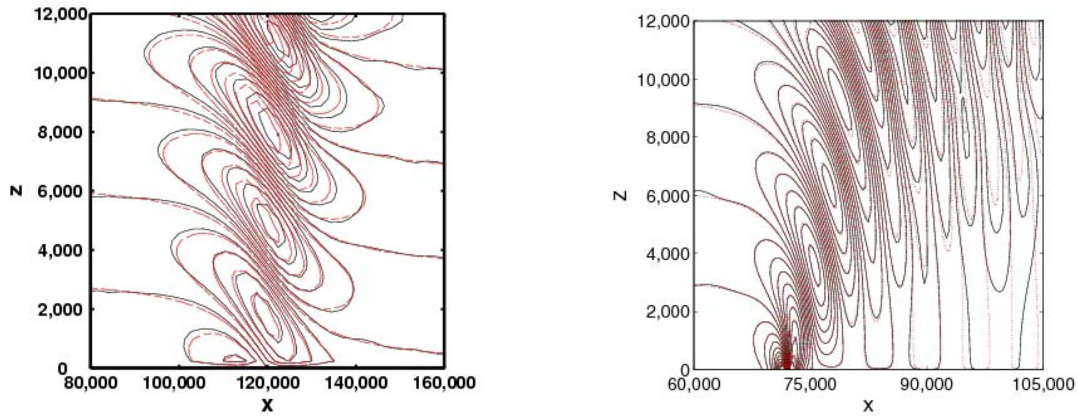
Mesoscale Nonhydrostatic Atmospheric Models. In Ref. [3] we present five mesoscale models using equation sets 1, 2, and 3, in conjunction with the SE and DG methods. For example, SE1 means that the SE method was used for set 1. Note that there is no DG1 because set 1 is not in conservation form and thereby cannot be used with the DG method. In Ref. [3] we show results for six test cases ranging from rising bubbles, density currents, to mountain wave problems; for brevity we only show two results in this report. Figure 1 shows the results for a non-smooth bubble rising in an isothermal atmosphere. Figure 1a (left panel) shows the potential temperature perturbation contours after 600 seconds. Note that this problem represents a very sharp discontinuity (shock wave) and is handled extremely well by all five models. Figure 1b (right panel) shows the profiles along 1000 meter height and here it is quite evident that the discontinuities are quite sharp. Another good result illustrated here is that these simulations were performed with semi-implicit (for DG3) and semi-implicit semi-Lagrangian (for SE1) methods which allowed for Courant numbers from 100 all the way to 800 to be used. This is in stark contrast to Courant numbers of 0.5 which are required by the explicit time-integrators (such as the 3rd Order Runge-Kutta method used for SE2, SE3, and DG2 models).



a) *b)*

Figure 1: Potential Temperature for 5 meter of a non-smooth bubble (shock wave) a) contours after 600 seconds and b) profiles along z=1000 meters for all five models. DG3 uses the semi-implicit method with Courant numbers of 100 while SE1 uses the HELSI method with Courant numbers of 800.

In Fig. 2 we show the vertical velocity contours for two mountain wave problems where the dashed red lines denote the analytic solutions while the solid black lines are the numerical solutions. Figure 2a (left panel) shows the results for the linear hydrostatic mountain wave and Fig. 2b (right panel) shows the results for the linear nonhydrostatic mountain wave. Note how accurately the numerical results agree with the analytic solutions.



a) *b)*

Figure 2: Vertical velocity contours showing the analytic solution (dashed red lines) and the numerical solution (solid black lines) for a) linear hydrostatic mountain wave problem and b) linear nonhydrostatic mountain wave problem. The results were obtained with the semi-implicit DG3 with a Courant number of 1.8 and the HELSI SE with a Courant number of 9.

In fact, comparing root-mean-square errors we show that all five of our models yield results that compare quite favorably with all the operational models currently in use. Furthermore, our results show that the most important thing required to achieve good results for this test case are the boundary conditions, followed by the equation set used. Specifically, set 2 (SE2 and DG2) is better than set 1 (SE1) while set 3 (SE3 and DG3) is better than set 2. Although the results between the SE and DG methods are very close, it is clear that the DG method outperforms the SE method in terms of accuracy but at the price of requiring more computational resources. Based on the results presented in Ref. [3] one would conclude that SE3 and DG3 are the best choices for the development of future models. However, if one takes efficiency into consideration, then perhaps the optimal choice is to use SE2 in conjunction with the hybrid Eulerian-Lagrangian Semi-Implicit (HELSI) time-integrators. Using the HELSI approach, we have been able to use Courant numbers as large as 9 for this problem.

IMPACT

NOGAPS and COAMPS are run operationally by FNMOC and is the heart of the Navy's operational support to nearly all DOD users worldwide. This work targets the next-generation of these systems for massively parallel computer architectures. NSEAM and its mesoscale cousins have been designed specifically for these types of computer architectures while yielding the same high-order accuracy as the current systems. Additionally, the new models are expected to conserve all quantities such as mass and energy which will greatly improve the capabilities of the Navy's forecast systems.

TRANSITIONS

Improved algorithms for model processes will be transitioned to 6.4 (PE 0603207N) as they are ready, and will ultimately be transitioned to FNMOC with future NOGAPS upgrades.

RELATED PROJECTS

Some of the technology developed for this project will be used immediately to improve the current spectral transform formulation of NOGAPS in other NRL projects. In addition, the work on the mesoscale models will help improve COAMPS.

REFERENCES/PUBLICATIONS/PRESENTATIONS

1. Flatau, M., and Giraldo F. X., 2007: Tropical Instability Waves and ITCZ Breakdown in the Eastern Pacific. *Geophysical Review Letters*, submitted.
2. Läuter, M., Giraldo F. X., Handorf D., and Dethloff K., 2007: A Discontinuous Galerkin Method for the Shallow Water Equations with Spherical Triangular Coordinates. *Journal of Computational Physics*, submitted.
3. Giraldo, F. X., and Restelli M., 2007: A Study of Spectral Element and Discontinuous Galerkin Nonhydrostatic Mesoscale Models: Equation Sets and Test Cases. *Journal of Computational Physics*, in review.
4. Giraldo, F.X., 2006: Hybrid Eulerian-Lagrangian Semi-Implicit Time-Integrators. Computers and Mathematics with Applications, Vol. 52, 1325-1342.
5. DeLuca, T., 2007: Performance of Hybrid Eulerian-Lagrangian Semi-Implicit Time-Integrators for Nonhydrostatic Mesoscale Atmospheric Modeling. *Naval Postgraduate School Master's Thesis.*
6. Restelli, M., and Giraldo F.X., 2007: A Conservative Semi-Implicit Discontinuous Galerkin Formulation for the Navier-Stokes Equations in Nonhydrostatic Mesoscale Modeling. *Journal of Computational Physics*, submitted.
7. Dea, J., Giraldo F. X., and Neta B., 2007: High-Order Non-Reflecting Boundary Conditions for the Linearized 2D Euler Equations. *Wave Motion*, submitted.